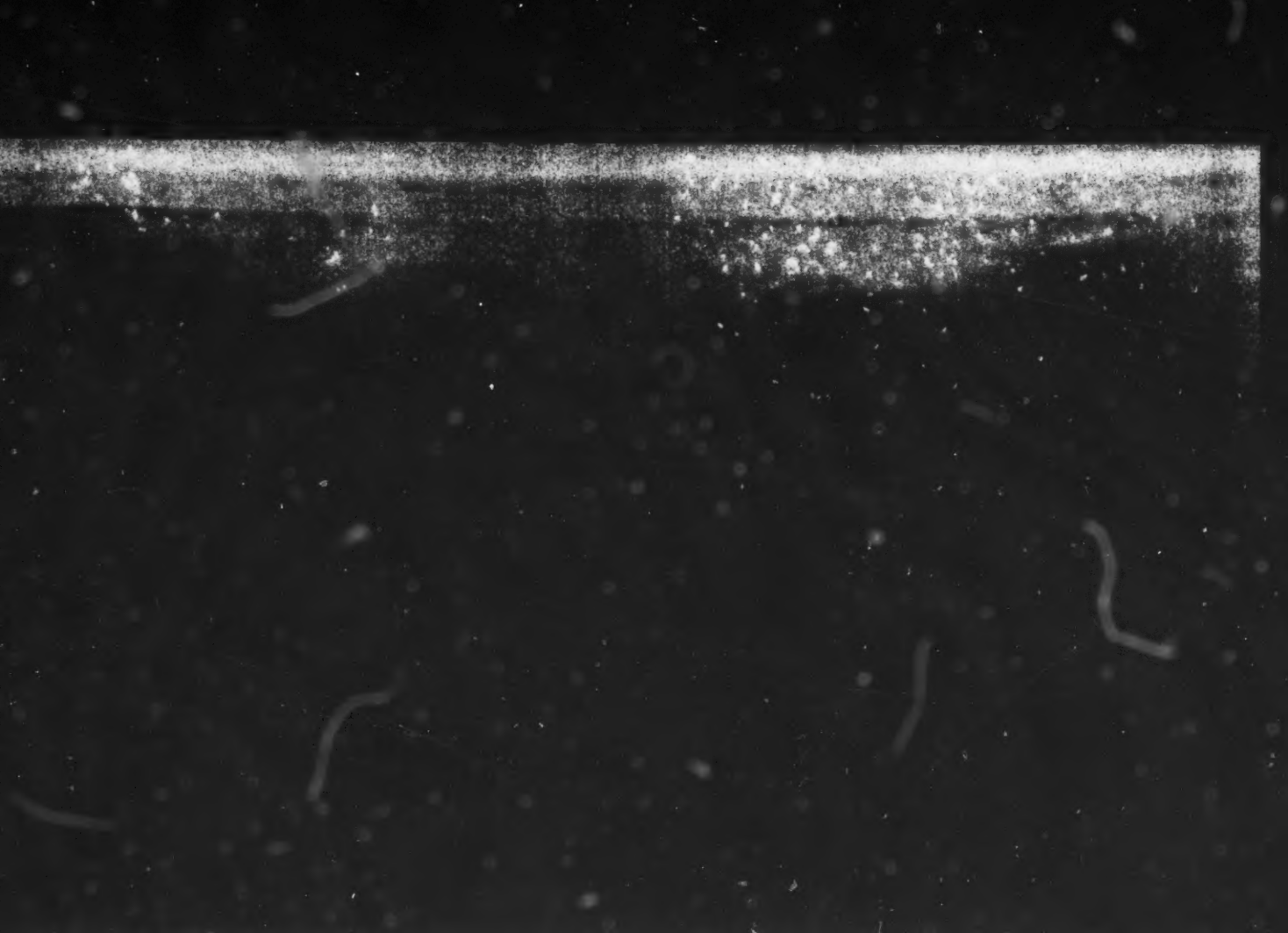

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2. BACKGROUND THEORY

2.1. Energy Balance and Ice Strength

The energy balance of a river ice sheet can be written as:

[1] $$Q_a = S_* + L_* + Q_h + Q_e + Q_p + Q_w$$

where Q_a is the heat available for melt, S_* is net short-wave radiation, L_* is net long-wave radiation, Q_h and Q_e are the atmospheric sensible and latent heat fluxes, Q_p is the precipitation heat flux and Q_w is the water-to-ice heat flux (all in W m^{-2}). Positive values indicate energy gains to the ice. In this study no precipitation occurred and Q_p is therefore ignored in [1]. Similarly, Q_w was small and is also not considered.

Heat transfers by convection and conduction produced by terms in [1] are all important to the thermal ripening and thinning of the ice cover which in turn cause a decrease in the overall strength and resistance of the ice sheet. Solar radiation, however, can also produce significant decreases in the internal strength of the ice. Upon reaching the surface, short-wave radiation is either reflected, consumed in melt or penetrates into the underlying ice where it is rapidly attenuated, depending on grain size, shape and orientation. After the internal ice temperature of the cover reaches the melting point, attenuated light produces melt at grain boundaries resulting in a decrease in ice strength (e.g. see Ashton 1983, Bulatov 1972).

2.2. Ice failure processes

River ice break-up is initiated and progresses by a variety of fracturing and fragmenting processes, including vertical and horizontal bending and crushing. The failure in each of these is dependent on some measure of ice strength. The borehole jack test is most representative of ice failure in compression.

2.2. Borehole jack

The borehole jack (Fig. 1) consists of a hydraulic cylinder which, when pressurized, pushes indentor platens into the walls of a borehole cored from the ice sheet (Fig. 2). Although the pressure required to indent the platen into the ice is representative of the overall ice strength in compression, the area surrounding the platen is comprised of several distinct zones: hemispherical adfrozen crushed, crushed, radially cracked, and elastic, each with unique material properties (Masterson 1983). In modeling jack behaviour, Masterson (1983) considered the adfrozen crushed zone to be part of the infinitely stiff indentor and conducted his analysis by examining the

Fig. 3 Coring on black ice strip.

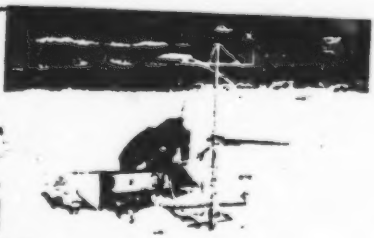

Fig. 4 Energy balance equipment

During indentation, applied hydraulic pressure and platen displacement were recorded on a strip-chart recorder.

3.3 Analysis

Following the methods used by Prowse and Marsh (1987) in a study of heat flows to river ice at the same study site, the fluxes of sensible and latent heat were calculated using bulk aerodynamic formulae. Vapour pressures were obtained by the Goff-Gratch and Teton formulations as reviewed by Sargent (1980, 1982). Values for surface roughness were obtained from wind measurements at two heights and under neutral conditions. All estimates were corrected for stable and unstable conditions following the method of Price and Dunne (1976). Applied hydraulic pressure was converted to platen pressure (principle stress σ_1) and plotted with platen displacement (δ) over time as illustrated in Fig. 5. Also shown is a σ_1 versus strain (strain at the platen-ice boundary ε_0), the peak of which is assumed to represent maximum ice resistance.

4. RESULTS

Snow depth decreased from approximately 0.45 m on April 11 to a mixture of ponded water and melting white-ice on April 24. With the removal of surface snow, some zones of columnar black ice became exposed (see Fig. 3). As shown in Fig. 6, surface melt was primarily driven by the radiation components although sensible heat dominated on a number of days. Security of the energy balance equipment required its removal on April 27 after which the total energy balance was estimated (Q_a; W m^{-2}) from daily air temperature (T_a; °C) and sunshine (I; h) data from the nearby (2 km distance) airport weather station. The equation relating these factors to the measured energy balance is:

depth) ice temperatures never fell below 0.6°C and remained at or near 0°C after April 17.

The peak σ_i values obtained from the bore-hole jack tests are plotted in Fig. 7 and show a steady decline from approximately 16.1 MPa to 8.8 MPa over an 18 day period. Notably, ice break-up occurred on the day after the final set of tests. The lower point on April 29 of 3.4 MPa represents measurements conducted in a strip of columnar black ice which became devoid of surface snow and white ice on April 24. Beginning on this date, a separate energy balance total ($Q_{a''}$; W m^{-2}) was calculated for this site using:

[3] $Q_{a''} = Q_{a'} (1 + R_S((1-\alpha_b)/(1-\alpha_w)-1))$

where R_S is the ratio S_*/Q_a established during the latter days of the energy balance experiment and, α_b and α_w are the albedo for black and white ice respectively. α_b was set to 0.17, a value found by Prowse (1987) for black ice in the early stage of decay. Based on the extended heat flow data, Fig. 8 was derived which shows the change in peak σ_i with the accumulated heat flow.

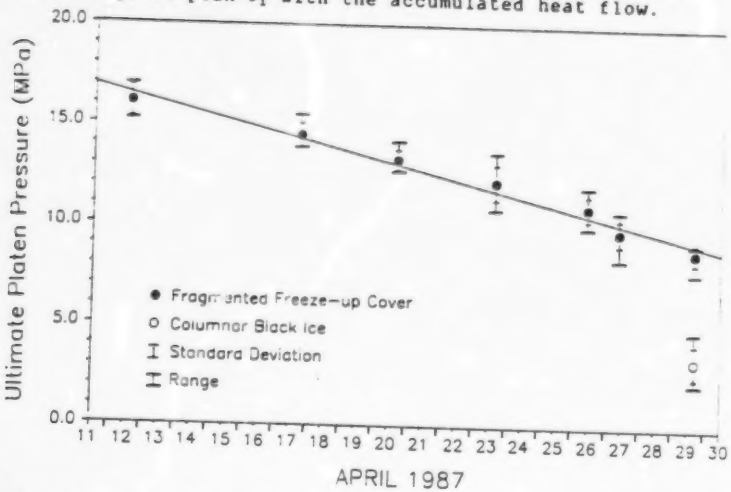

Fig. 7. Change in peak platen pressure over time. Circles represent mean test values. Bars show variability. Regression line for fragmented cover data is $\sigma_i = 60.214 - 0.426d$, where d is Julian day, $r^2 = 0.98$.

rate of load application could perhaps solve this problem.

In view of the results, two logical extensions to this analysis could be made. Firstly, since strength is known to vary as a function of loading history (e.g. Gold 1977, Sinha 1982) it should be considered in calculating the yield strength. Second, because the ice sheet was essentially 0°C most internal changes in ice strength were believed to have occurred from radiation penetration. Hence, changes in strength should be related to short-wave heat flow at the test depth, or more specifically to total melt or changes in ice porosity as proposed by Ashton (1983).

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STRENGTH AND ENERGY BALANCE OF DECAYING RIVER ICE

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ABSTRACT

During melt periods, river ice can experience significant changes in strength that, at least partly, determine the severity of break-up conditions. Because of the weakness of ice during this period, in situ strength tests are mandatory and relatively scarce. This paper reports on the use of a borehole jack to determine changes in ice strength during an 18 day pre-break-up melt period on the Liard River, Northwest Territories, Canada. Concomitant measurements were made of the river-ice energy balance. Strength, as measured by ultimate platen pressure, decreased by approximately 50% at a rate of 0.4 MPa/d or 0.07-0.08 MPa/MJ m^{-2} d^{-1}. Suggestions for further analysis and future experiments are included.

1. INTRODUCTION

Ice strength plays a critical role in the initiation of river ice break-up and determines the stress imparted to structures during break-up. In general, break-up occurs when downstream forces exceed the resistance operating to keep the ice sheet in place and intact. During melt periods, rising stage and velocity produce an increase in the downstream forces but the resistance can also decrease, particularly when the ice cover detaches from support zones, such as banks and shoals, or when the strength of the ice sheet decreases. Changes in strength result from overall warming of the cover and from radiation melt within the ice sheet. An ability to measure such changes in ice strength could greatly assist in the prediction of the timing and severity of break-up.

Because of the weakness of the ice during the pre-break-up period, strength measurements must be carried out in situ. Past experiments have relied on small-scale compression, cantilever beam and penetration tests with varying success. This paper reports on the use of a borehole jack during an 18-day period immediately preceding break-up. The results are related to detailed energy balance measurements conducted over the same period.

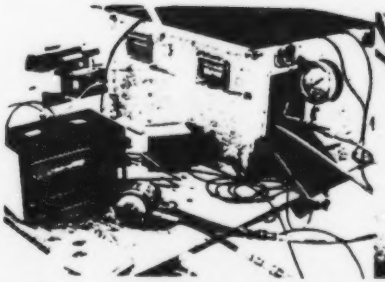

Fig. 1 Borehole jack test equipment

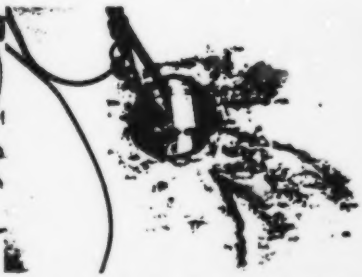

Fig. 2 Jack placed in borehole

expansion of a spherical hole in an infinite elastic-plastic-brittle medium. In an attempt to make the borehole jack test results quantitatively useful, Sinha (1987) has related them to results from unaxial compression tests.

3. SITE, EQUIPMENT AND METHODOLOGY

3.1. Study site

The study was carried out in spring of 1987 on the Liard River near its confluence with the Mackenzie River (61°53°N, 121°22°W). The Liard River drains 277,000 km² with a mean annual discharge of 2,580 $m^3 s^{-1}$ (Environment Canada 1980). Mean air temperatures rise above freezing on April 19 and climb to 7°C by May 7 (Environment Canada, unpublished). Break-up of the Liard River near its mouth occurs in early May with the first deterioration of the snow and ice cover beginning in late April. Details of the process of ice decay and clearance at this site can be found in Prowse (1984, 1986). Ice conditions in 1987 primarily consisted of a surface dominated by a rough freeze-up cover (white ice) interspersed with localized zones of columnar black ice (Fig. 3), all covered at the beginning of the experiment by half-metre deep snow.

3.2 Equipment and Methodology

Reports of previous studies conducted at this site (Marsh and Prowse 1987; Prowse and Marsh 1987) detail the instruments employed in the 1987 energy balance study (Fig. 4). A 20-point grid was established to monitor changes in snow depth and density. Test area for the borehole jack was 50 m upstream from the energy balance equipment. Sites, separated by a minimum of 15 m and arranged in a grid pattern, were used for a series of 5-10 measurements. Eight series of tests were conducted over the eighteen day period. For each measurement, the jack was set 0.5 m deep in ice that averaged 1.0 m thick.

[2] $Q_a' = 1.780 + 0.275\ I + 0.435T_a$

with an r^2 of 0.63. Daily heat flow to the ice cover ranged from 0.13 to 9.94 MJ/m²/d, increasing steadily over the two weeks prior to break-up. Internal (0.5-m

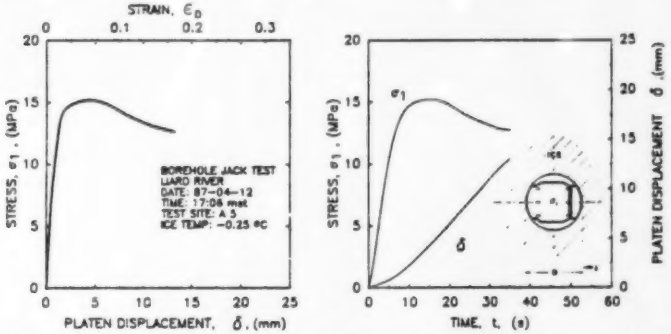

Fig. 5. Sample of stress versus displacement curve (left) and, stress and displacement versus time curves (right). Insert shows schematic of borehole jack in ice.

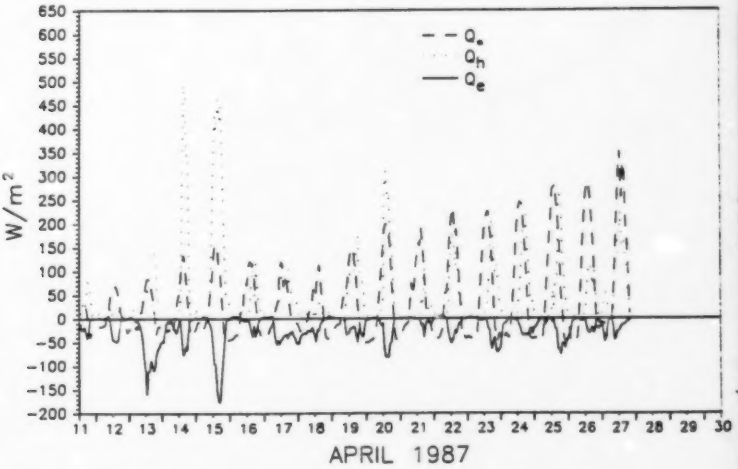

Fig. 6. Energy balance components. Symbols defined in the text.

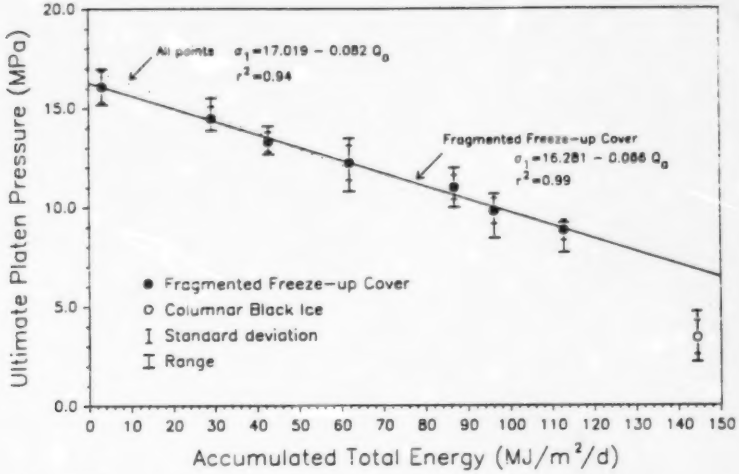

Fig. 8. Change in peak platen pressure with accumulated heat flow. Separate regressions shown for all data points and the fragmented cover data only.

The black-ice point essentially represents a higher degree of melt, a condition which would also eventually develop for the surface white ice zones if melt conditions prevailed long enough (i.e. melt of surface white ice and exposure of underlying black ice).

5. DISCUSSION AND RECOMMENDATIONS

The results of this initial experiment suggest that the borehole jack provides an index of the decrease in ice strength during the pre-break-up period. Unfortunately, due to the lack of variability in melt conditions and/or the frequency of strength testing, it is not possible to test whether these changes are more highly correlated to accumulated heat flow than just elapsed time. Furthermore, although it could be argued, based on Fig. 8, that heat flow under-predicts the decrease in strength at an advanced stage of melt (as represented by the black ice sample), it is believed that the test on the black ice surface did not meet some of the stress-distribution criteria assumed for the test. In particular, it was observed in the field that indentation of the decaying black ice only resulted in a rearrangement of the columnar crystals. The stress fields as assumed by Masterson (1983) were not replicated at this extended state of decay. Modifications to platen design and/or

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